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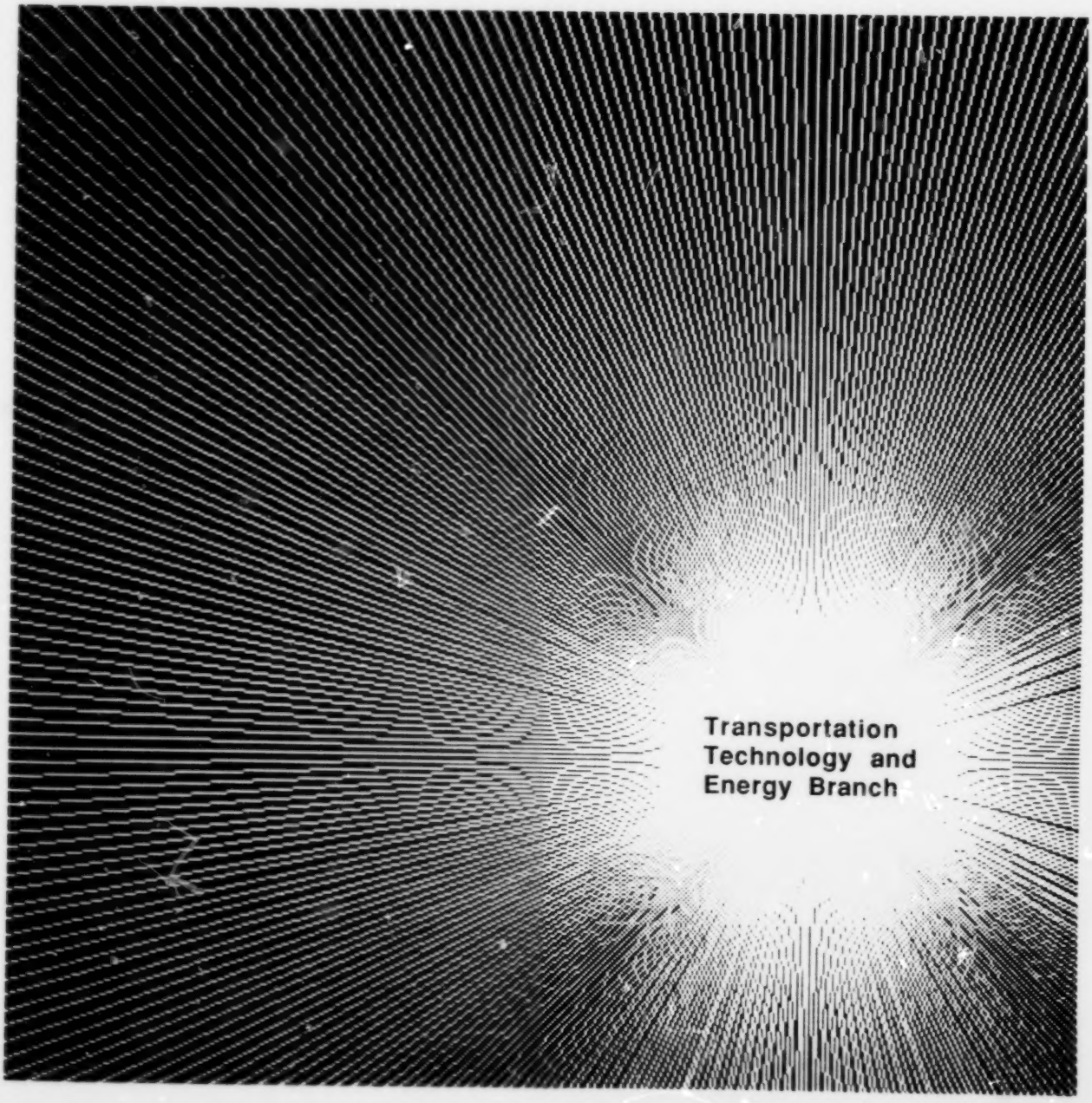

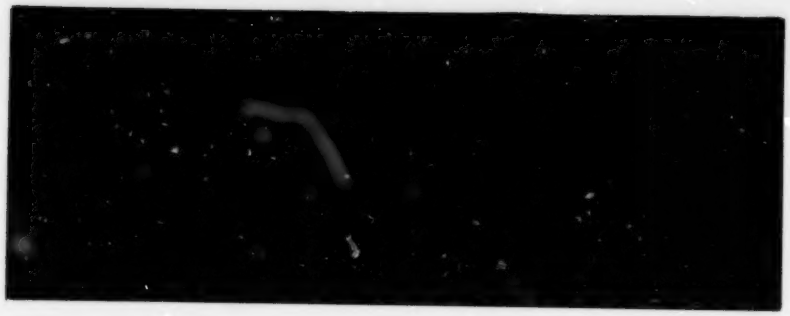

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Laboratory Evaluation of a Prototype Vision System for Automated Rail Profile Measurement

RT-91-01

Technical Report Documentation Page

Laboratory Evaluation of a Prototype Vision System for Automated Rail Profile Measurement

Prepared by: D. Leung

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Abstract: A prototype vision system for measuring rail profiles was tested for data consistency and accuracy on a section of test track.

This report presents the test results and discusses several areas where the effectiveness and performance of the system can be enhanced with a few improvements. The report concludes that a vision-based rail profile measuring system will provide an efficient and effective alternative to conventional rail profile measurement methods.

Recommendations are also made regarding further work.

Key words: Machine vision, image processing, automation, rail profiles, rail maintenance and planning, rail wear

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Laboratory Evaluation of a Prototype Vision System for Automated Rail Profile Measurement

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1/ INTRODUCTION

The Rail and Advanced Transportation Systems Office (RATSO) of the Ministry of Transportation has been engaged in an R&D project on the application of machine vision technologies to wheel/rail wear monitoring. The project has three major goals:

1/ to evaluate the feasibility of applying the technology in the rail sector,
2/ to promote appropriate use of the technology by rail properties, and
3/ to foster the development and manufacturing of machine vision products by the private sector in Ontario.

Currently two machine vision systems are commercially available for the monitoring of rail wear. These are primarily designed for use on freight rail. To date, two major railroads and one transit property have acquired installations of these systems. Nonetheless, concerns exist as to their accuracy, reliability, and effectiveness, particularly for transit applications [1].

To address some of these concerns, a test program was initiated in the spring of 1988. In this program, a prototype rail profile measurement system, the RIMS (Rail Inspection and Measurement System), which had originally been designed for demonstration use in a stationary indoor environment, was adapted for operation on tracks and subjected to a series of track tests. The program was expected to help build confidence in the technology, allow RATSO to gain more hands-on experience and insights into the application of the technology, and pave the way for further testing and/or development of the technology.

This report reviews the capabilities of the RIMS, presents the findings of the test program, and provides a few suggestions regarding improvement in the technology and recommendations concerning further work.

2/ OBJECTIVE

The objective of the test program was threefold, as follows:

- to determine the accuracy that can be attained by the existing system;
- to determine the repeatability and consistency of measurements using the system; and
- to gain experience with the system with regard to system errors, performance constraints, deficiencies, and the effects of various factors including ambient conditions and rail surface conditions.

3/ DESCRIPTION OF RIMS

The RIMS was originally acquired by RATSO in 1987. It was primarily assembled from off-the-shelf components with a view to simplify maintenance and repairs should such needs arise. It employs a constant incandescent light source. Image processing is primarily performed by software. Figure 1 illustrates the conceptual set-up of the RIMS.

3.1/ Hardware

The system hardware consists of three main components:
1/ a sensor,
2/ a 80286-based Compaq portable personal computer, and
3/ an analogue monitor.

The sensor is comprised of a single light source and a single CCD video camera, housed in separate cabinets that are rigidly mounted on two heavy gauge aluminum angles. A layout of the sensor is shown in Figure 2.

The light source is a 100 W, 12 V DC incandescent lamp. With the aid of lenses and mirrors, it projects a narrow band of light onto the railhead from both the gauge and field sides of the rail. The width of the light band is about 5 mm.

Also employing lenses and mirrors, the camera is able to "look" at both the gauge and field sides of the railhead so that a complete profile of the railhead can be captured through merging two half images of the railhead section. Its sensitivity to light is adjusted by the operator of the system by entering an appropriate "threshold value" into the computer. With a resolution of 512 (horizontal) x 384 (vertical) and a design horizontal field width of four inches, the resolution of the image achievable by RIMS is 0.30 mm while theoretical measurement accuracy is +/- 0.50 mm (0.020 inch).

The portable computer is equipped with commercially available image processing boards that serve to capture the image of the rail profile as detected by the camera, digitize it, and store the digital data onto the hard disk of the computer. The computer also allows digitized profiles to be displayed on the built-in monitor (Figure 3).

The analogue monitor is primarily used for live display of the rail profiles that are being measured so that a visual inspection of the quality of the profile images to be recorded is possible before actually processing and storing the resulting data (Figure 3).

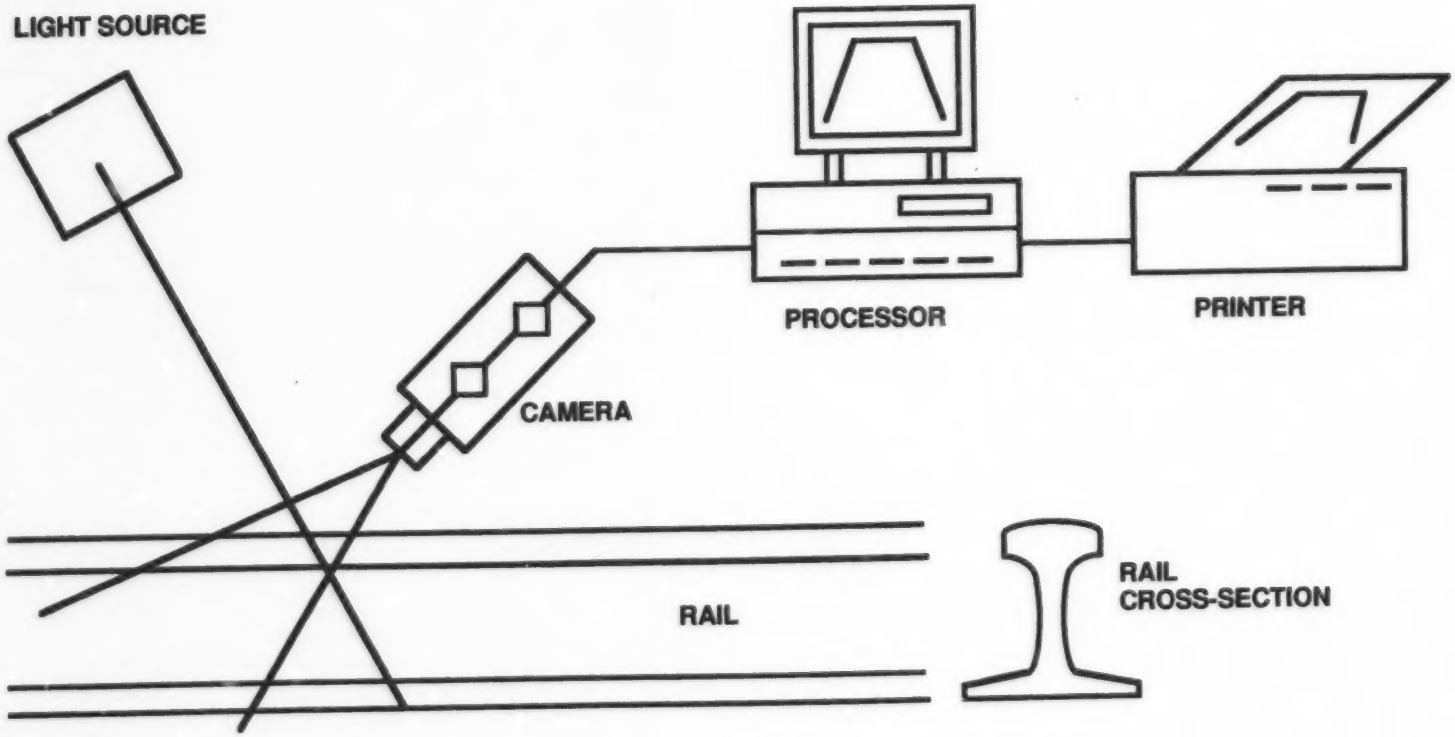


Figure 1/ A Conceptual Set-up of the RIMS

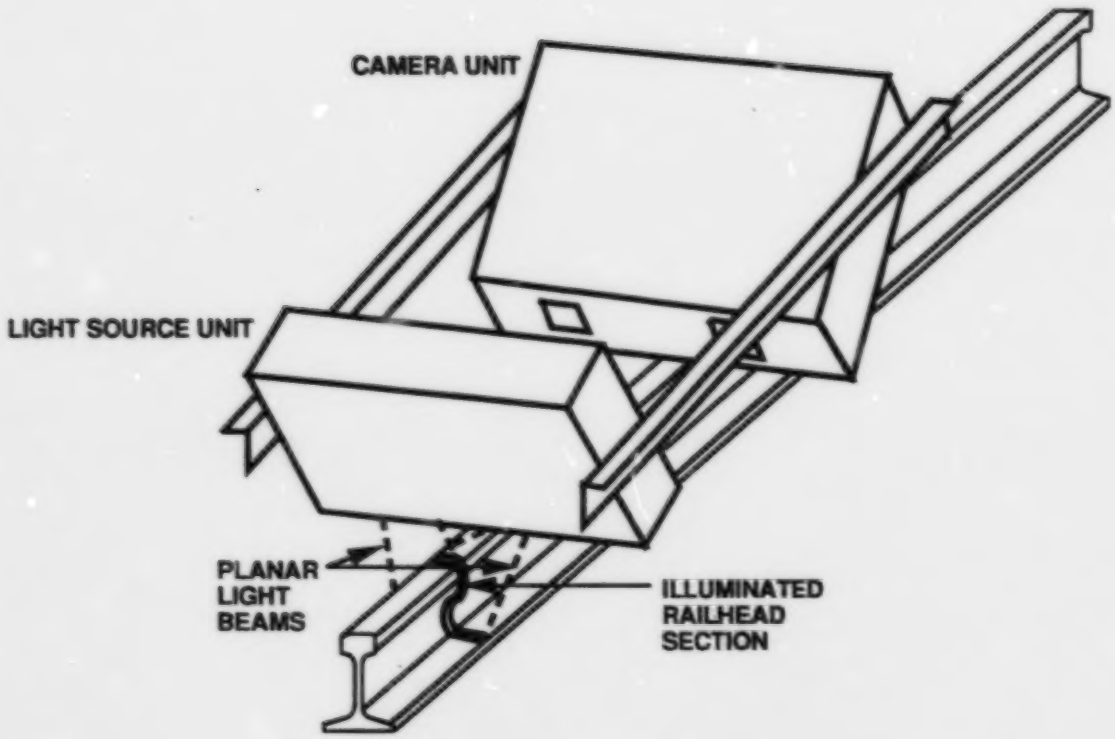


Figure 2/ Layout of the RIMS

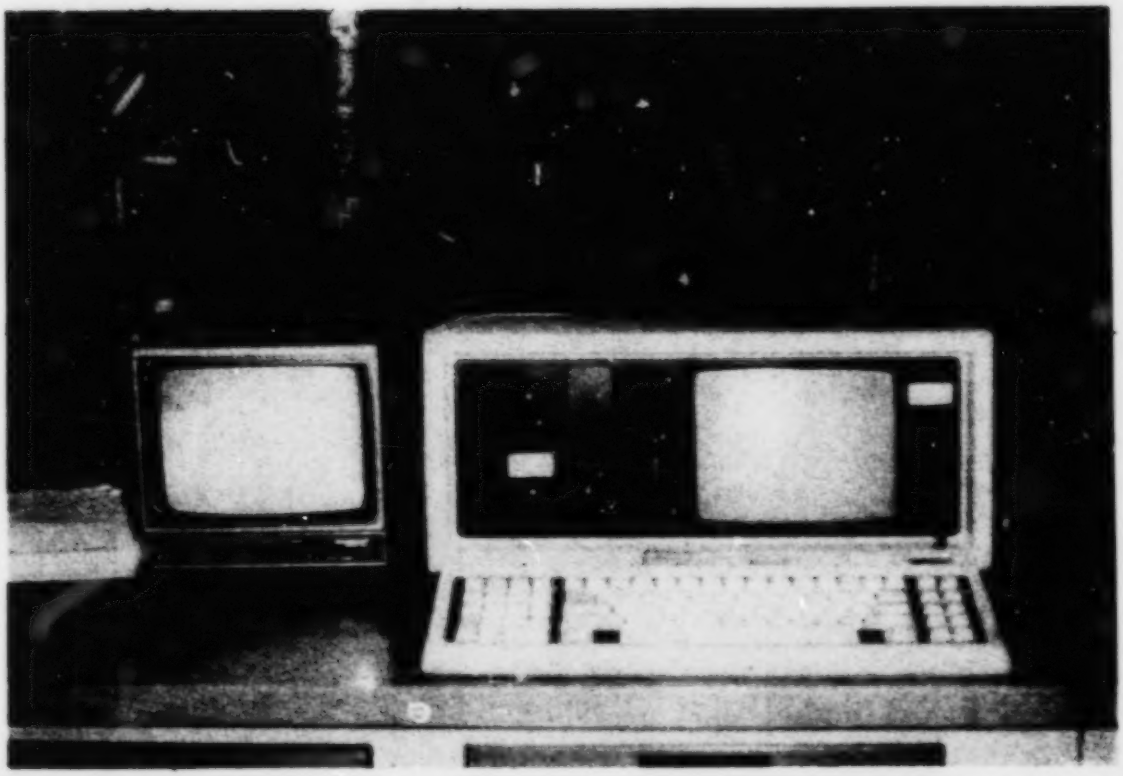


Figure 3/ Computer and Analogue Monitor Components of the RIMS

3.2/ Software

Capabilities of the RIMS software include:

1/ Capturing the profile image and reducing the data to an array of relative x-y co-ordinates depicting the profile. This reduced data set may then be stored. However, data that may not pertain to the profile (such as may be caused by ambient light) may still be included.

2/ Displaying a processed rail profile on the computer monitor or the analogue monitor.

3/ Calculating the following pre-defined parameters of the rail profile:
   a) railhead height
   b) railhead half-width on the field side
   c) railhead half-width on the gauge side
   d) railhead height loss with respect to a new nominal rail section
   e) flange loss on the field side of the rail section with respect to a new nominal rail section
   f) flange loss on the gauge side of the rail section with respect to a new nominal rail section

These calculations are made by first locating the lowest point on at least one side (generally the unworn side) of the captured profile image and using it as a reference point. Railhead height calculations are made along a vertical centre-line located by a given horizontal offset from this reference point. The field-side and gauge-side railhead half-widths are then measured from the above-mentioned centre-line at the gauge point level of the railhead.

This methodology makes it quite clear that capturing the lowest point(s) of the railhead profile image is critical to the accuracy of the system.

Typically, image processing times are about 20-25 seconds from the start of capturing an image to displaying the digitized profile on the computer monitor and generating the above-mentioned wear parameters.

4/ TEST SET-UP

The test set-up consisted of the RIMS, an aluminum carriage on rollers, and a 10-foot long section of subway track.

Supplied by TTC, the test track had been taken out of a curve section and was complete with wooden ties. One of the rails exhibited considerable wear, while wear on the other rail was light.

Test sections were marked on the web area of the lightly worn rail. A mechanical pointer was attached to the aluminum carriage to locate station positions. The rail surface was cleaned of rust formations with a solvent and a grinder to present a shiny surface similar to that of an in-service rail.

The carriage was fabricated from aluminum sections for lighter weight. It consisted of a square frame section and a triangular frame section. The square section was equipped with two vertical legs, each of which was fitted with a flanged and removable steel roller. These legs would ride on the rail that was to be measured. The sensor of the RIMS was supported on this frame; vertical clearance between the sensor and the railtop was maintained at about three inches.

The triangular frame section was also equipped with a vertical leg with a flanged steel roller. This leg was adjustable in position laterally and would ride on the other rail for support. The adjustability allows adaptations to different track gauges and allows control of flange clearance. Other hardware components of the RIMS, such as the computer and the analogue monitor, may also be supported by the triangular frame.

Figure 4 shows the schematic of the carriage. Figure 5 shows the actual test set-up, while Figure 6 shows a close-up view of the light band projected onto the rail by the sensor.

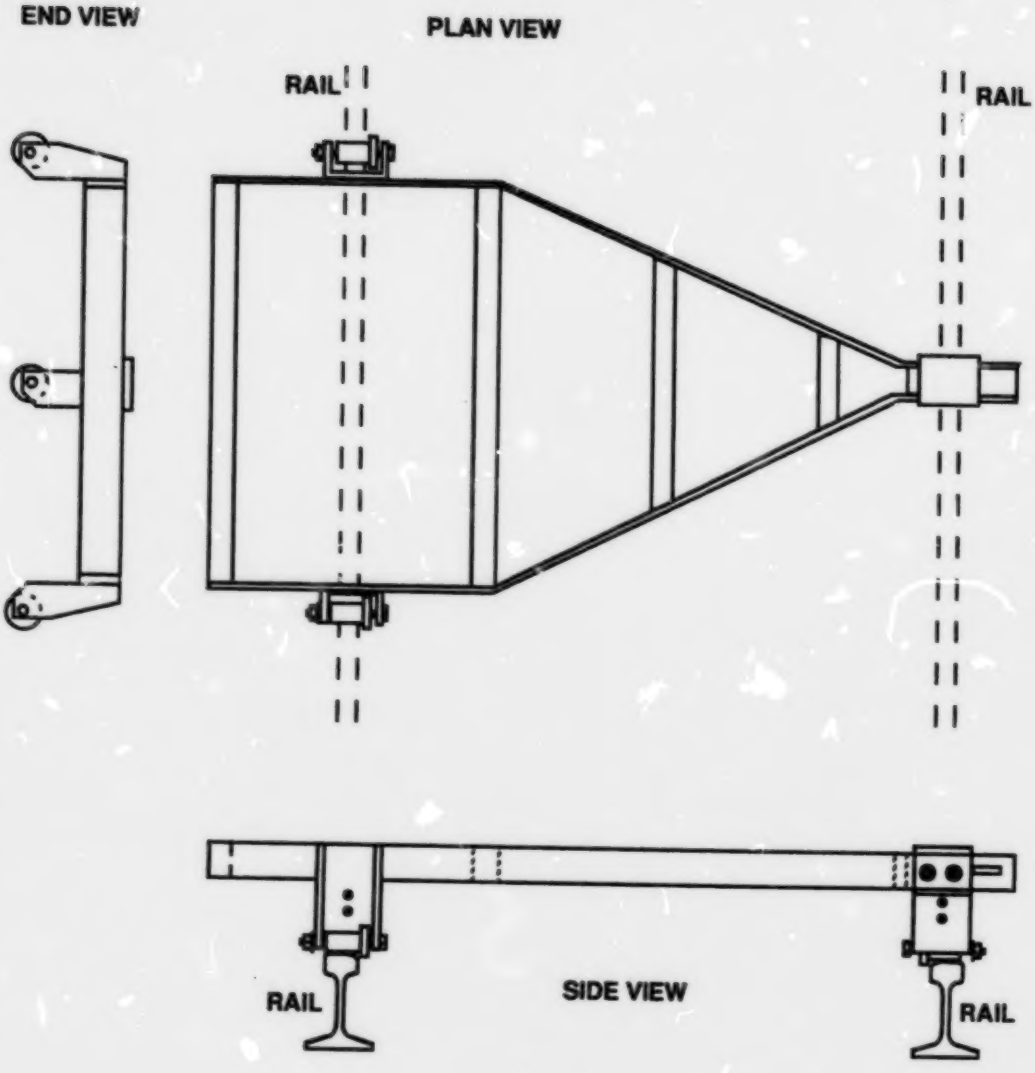


Figure 4/ Layout of the Carriage

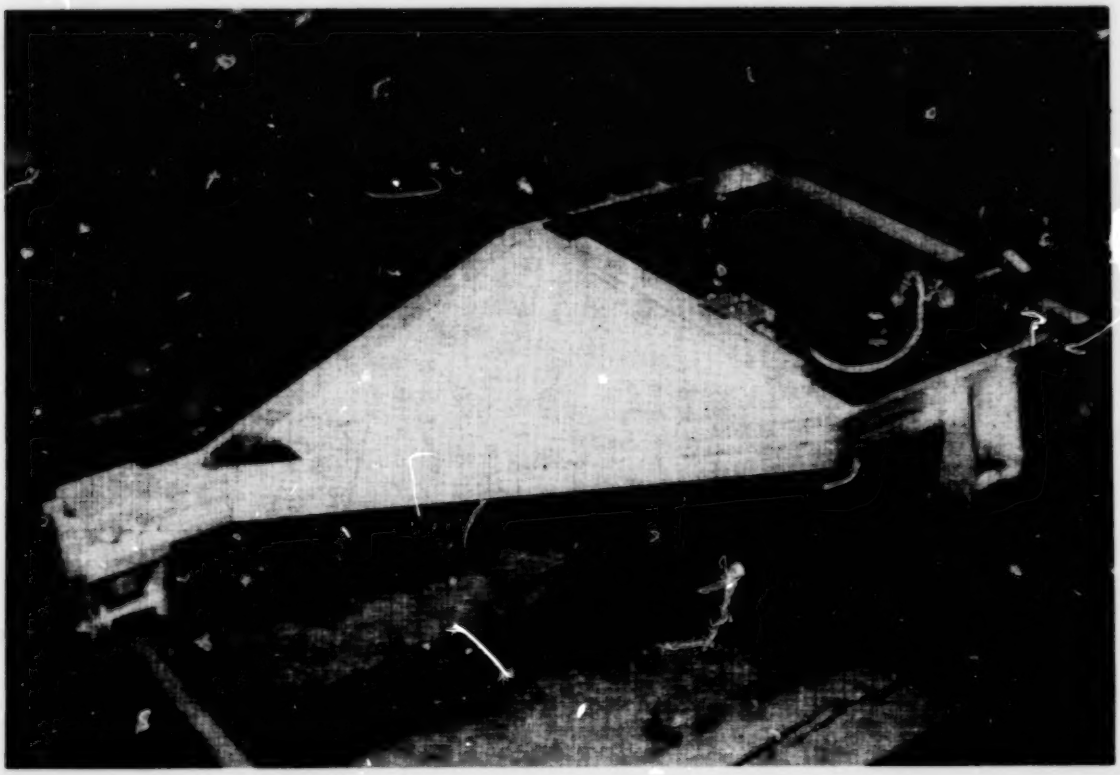


Figure 5/ Actual Test Set-up

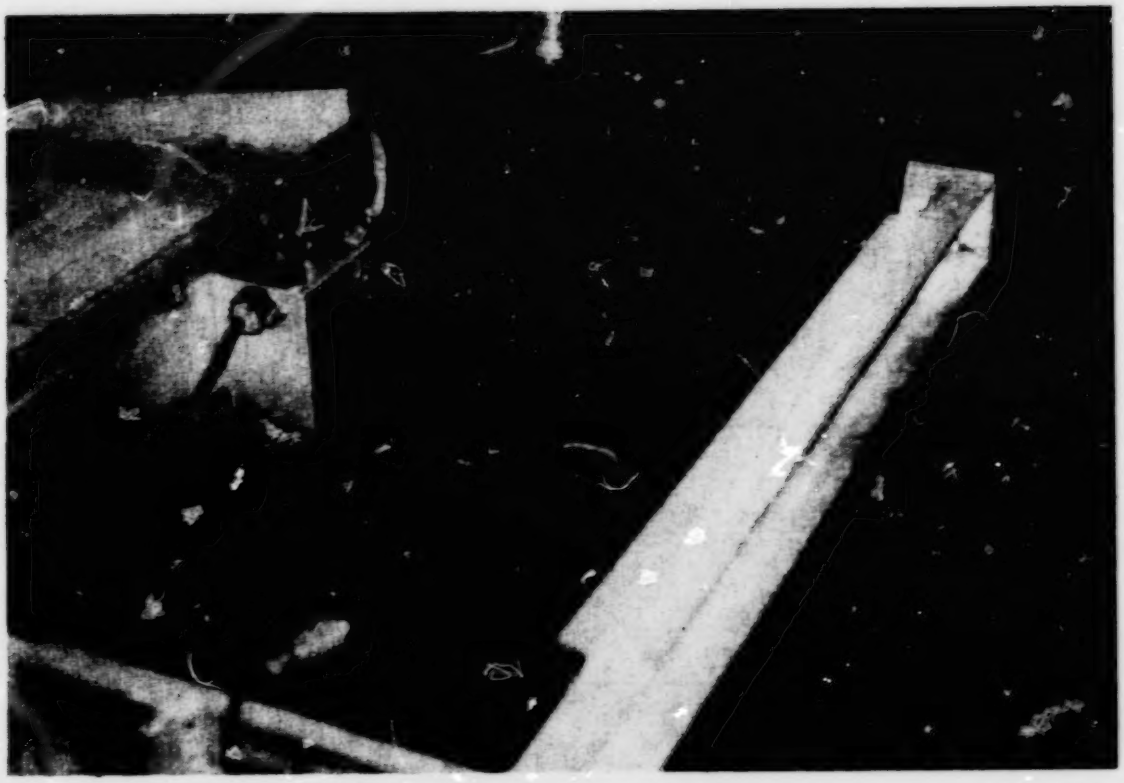


Figure 6/ Close-up View of Light Band Projected onto Rail

5/ TEST DESCRIPTIONS

Although the RIMS has been designed primarily for demonstration purposes in an indoor laboratory environment, both indoor and outdoor tests were carried out on the system.

Each image taken of the rail section was evaluated for the six wear parameters detailed in the section "Description of RIMS."

Each category or group of tests had a different objective. These tests are briefly described here:

5.1/ Indoor Tests

Four categories of indoor tests were performed:

- **Category A**

The objective was to test for accuracy and repeatability of data with minimum or no change in ambient conditions.

An optimum threshold value was selected by running the sensor over each of the six test stations and visually inspecting the quality of the rail images as displayed at the stations. The sensor was then positioned at each station, and the flange clearance with respect to the test rail set to zero. Six images were then taken in succession.

- **Category B**

The objective was to evaluate the effect of various threshold values on profile measurement.

A workable range of threshold values was first selected by running the RIMS over all six test stations and visually inspecting the quality of the images as displayed on the analogue monitor. Under the prevalent conditions, the workable range was found to be between 20 and 45. Below this range, there would be excessive spurious data due to ambient light; above it, portions of the profile being inspected would be lost.

At each station, flange clearance with respect to the test rail was set to zero.

Six images were then taken at each of the stations, each image at a different threshold value.

- **Category C**

The objective was to determine the magnitude of measurement errors due to random yaw orientations of the carriage with respect to the rail.

The carriage was initially set with a flange clearance of about 12 mm with respect to both rails. It was then rolled up to each station from the starting end of the rail and an image taken of the rail section. This procedure was repeated six times for each test station.

• Category D

The objective was to evaluate the feasibility of a low-speed mode using the existing RIMS.

The carriage was initially set with a flange clearance of about 12 mm with respect to both rails.

To generate realistic low-speed conditions, an operator would push the carriage across each station while another operator would take an image of the rail as the sensor crossed the station. It was estimated that the resulting speed of the carriage was about a fast walking pace of two to three miles per hour.

5.2/Outdoor Tests

A limited number of outdoor tests were carried out with the RIMS, with much less success.

It was found that even with the sensor and the rail area that would fall within the fieldwidth of the camera shrouded completely, the light source was not powerful enough to allow proper image data to be generated. (High threshold values had to be resorted to in order to "filter out" ambient light effects; however, most of the illuminated profile was also lost.)

Replacing the 100 W lamp with a 250 W, 24 V DC lamp brought some improvement: the required threshold value was lower (down to about 90 from the value of 150 that would have been needed with the less powerful lamp) and loss of profile was also reduced. However, spurious light data were still excessive and the quality of the profile image was still barely acceptable. There was also a considerable build-up of heat in the cabinet housing the lamp and in the power cable. For these reasons, the outdoor tests were discontinued.

6/ TEST RESULTS AND OBSERVATIONS

Results of head height losses, field side, and gauge side flange losses, plus the corresponding standard deviations, are presented in graphical form in Appendix 1.

Appendix II shows several typical "good" railhead profiles obtained, while Appendix III shows a few "bad" profiles from Test Category B. It is noted that for the latter, some of

which still provide excellent profile definition, (indicated by the scattering of "dots") a more rigorous algorithm would be needed for accurate calculations of the desired wear parameters.

These test results are discussed by category as follows:

• Category A

The test results show that except for the head loss parameter for test station 6, the maximum difference between any two measurements for the same parameter over all six test stations was less than 0.35 mm (it is noted that the resolution of the video image is about 0.30 mm); they also show that while station 6 exhibited the greatest standard deviations in the head loss parameters, none exceeded 0.23 mm.

This basically indicates that with proper lighting, good repeatability and consistency of data are achievable.

• Category B

In this test category, preliminary tests indicated that at threshold values lower than 20, the sensor would pick up too much ambient light and would cause the existing software to either yield grossly wrong wear parameters or fail to calculate.

It was therefore decided to use the range of 20-45 for the tests. Despite this limited range of threshold values, it was found that at values higher than 35, certain test sections would fail to yield proper measurement data, and at anything higher than 45, the software would simply fail for all test sections.

Given the limited range of variations in the threshold value, standard deviations for gauge-side and field-side flange losses were less than 0.30 mm, while the head loss standard deviations ranged from about 0.55 mm to over 0.90 mm. The much greater error in the head loss parameter is understandable in view of the fact that the head height was referred to a horizontal baseline defined by the lowest points on either side of the rail head, which would be prone to errors in the absence of proper illumination.

These findings seem to suggest a considerable performance limitation for vision system designs that employ traditional light sources for illumination, and a need for more sophisticated numerical analysis procedures.

• Category C

The results of this test category, which were obtained with a prescribed flange clearance of 12 mm, show standard deviations of less than 0.25 mm in all three wear parameters while the maximum discrepancy between any two wear measurements did

not exceed 0.67 mm (the theoretical accuracy of the RIMS is about 0.50 mm). It appears to suggest that random yaw orientations of the sensor with respect to the rail would not significantly affect the accuracy of the system.

This would imply that there is not a great need for a referencing system that would allow corrections in the wear data (at least so for a system with a theoretical accuracy of no better than 0.50 mm). However, it must be noted that for a system that operates on a rail vehicle moving at high speeds, the lateral movements of the rail could lead to increased errors so that corrections may be required to maintain an acceptable level of accuracy.

• Category D

Results for these simulated "dynamic" tests show maximum standard deviations of less than 0.35 mm for head loss measurements and of less than 0.25 mm for rail width loss measurements.

This suggests that a low-speed operation mode is feasible using a simple and low-cost vision system configuration that employs a constant light source for illumination. A rail wear measuring routine that utilizes a similar mode of operation could conceivably be incorporated into existing track inspection and maintenance procedures.

7/ DISCUSSION

Several issues that are of concern in the use of machine vision in rail wear monitoring have been identified by the test program:

7.1/ Light Source Improvement

The vision system used in this test program is equipped with a 100 W, 12 V DC incandescent lamp. This light source was found to be acceptable only for low ambient light conditions. Even with a more powerful 250 W lamp, and with complete shrouding of the sensor, excessive light filtering via the threshold settings is needed which results in a loss of parts of the rail profile, especially in areas where rust formations exist. Existing production designs employ traditional light sources such as xenon light. Therefore, these designs tend to rely on sophisticated numerical analysis to obtain good profile measurements. This approach appears to be emphasizing image processing. As a result, potential problems with ambient light still exist.

Furthermore, the width of the light section produced by these light sources on the railhead invariably exceeds 5 mm (the width is close to 20 mm in one current design), thereby producing a system error that would severely restrict any improvement in the accuracy of the respective systems. These light sources are also not very effective in generating a uniformly illuminated profile for typical rail sections, which generally

exhibit uneven surface conditions such as shiny patches over the tread area and rust formations on the flange areas. This could lead to measurement errors.

Another possible source of measurement error also exists with these lighting techniques: there is no mechanism to ensure that two measurements taken for a given track location would be taken under the same or comparable illumination. Thus, it is conceivable that in a field application during the daytime, ambient light conditions may vary so greatly that measurements taken for the same track location may exhibit significant discrepancies even though no wear may have actually occurred.

A different approach in which emphasis is placed on ensuring a high quality light source may yield more success. Such an approach would reduce the amount of numerical analysis that would otherwise be required for generating accurate measurements, thereby improving throughput. A laser light source coupled with an appropriate filter may be suitable.

7.2/ Software Improvement

The existing software relies on a high quality image for successfully generating the selected wear parameters. It has been demonstrated in this test program that any amount of spurious data such as may be caused by ambient light conditions could disable the software. In view of the fact that the presence of spurious data is a likely occurrence, it may be desirable for the operator to be able to visually examine the digitized image data, erase the spurious data as needed, and then submit the clean data for measurement calculations.

In addition, software (and hardware) may also be required to ensure that measurements are evaluated under comparable illumination conditions.

7.3/ Needs and Requirements of Transit Properties

The currently available vision systems for rail wear measurement have been designed primarily for mainline applications. They are capable of operating at high speeds (up to 60 mph), a critical requirement for the major railroads. As it is practically impossible to ensure that repeat measurements be made at the very same locations between intervals; an indeterministic approach is needed for processing the measurement data in assessing wear patterns, and predicting wear trends. This basically means that large volumes of measurement samples would be needed.

In contrast, the needs and requirements of transit properties with respect to the use of machine vision are very different. First, trackages are generally small for the average property. Second, most of the other routines included in existing track maintenance programs, such as inspecting the conditions of ties and ballast, still need to be manually performed. Third, tracks on transit properties are invariably laden with

trackside equipment or fixtures, which may present various difficulties. These characteristics of a typical transit property imply that dynamic operation at high speeds may not be needed.

The lesser emphasis of transit properties on dynamic operation may mean that a less sophisticated, and hence less costly, vision system may be adequate. A system mounted on a dolly, which may or may not be motorized, or attached to an existing work car is a strong possibility. The routine can be incorporated into existing track maintenance programs without additional demands on labour resources. Such a system may also be expanded to perform other tasks such as track gauge measurement.

Based on RATSO's experience with the RIMS, it is thought that a workable turnkey vision system for rail wear monitoring on a transit property can be developed for under $150,000. Once the development is completed, the cost of manufacturing additional systems will be much lower.

8/ CONCLUSIONS

Based on the results presented above, the following conclusions can be drawn:

1/ Results have indicated that under adequate lighting conditions, discrepancies between measurements obtained for the same rail location were within the theoretical accuracy of about 0.5 mm of the system. This is a strong attestation to the accuracy that one can achieve with the existing system for operational use.

2/ For most measurements, the associated standard deviations were invariably less than 0.25 mm. This reflects a high degree of repeatability and consistency in the measurements.

3/ Results from the dynamic simulation tests indicate a feasibility of using the existing system in a low-speed operation for greater efficiency.

4/ The existing system appears to be quite adequate for indoor or night-time operation, giving very good measurements, while in outdoor daytime applications, ambient daylight would present a serious problem. This however does not appear to be a significant deficiency for applications on transit properties, where night-time operation is typically preferable for most track maintenance work.

Based on the above, it is strongly felt that the RIMS vision system, in its present form, can be realistically used on a transit property. One possibility would be to operate the system in night-time as part of the property's track inspection and maintenance program.

9/ RECOMMENDATIONS

In view of the findings of the test program presented and discussed in the foregoing, the following recommendations are made:

1/ Further testing of the RIMS on a transit property is recommended. This would allow the system to be exposed to more realistic and generally more adverse track conditions, thereby allowing more experience and insights to be gained, and would further reinforce confidence in the performance of the technology in automated rail wear monitoring.

   The Toronto Transit Commission is a logical choice for the recommended testing. Discussions should start as soon as possible with TTC to agree on co-operation and commitment.

2/ A new development project should be initiated after additional testing of the RIMS on a transit property is completed. This development should be specifically aimed at a low-cost vision system for rail wear monitoring that will resolve the shortcomings of existing designs of the technology, and address the unique needs, requirements, and expectations of a typical transit property.

The co-operation and/or participation of the Toronto Transit Commission will be critical to the success of such a project. The project should also involve a Canadian technology company in order to foster development and/or manufacturing opportunities among the domestic private sector.

10/ REFERENCE

[1] Leung, D.K.W., "Application of Machine Vision to Wheel/Rail Maintenance," the 9th International Wheelset Congress, Montreal, Canada, September, 1988.

APPENDIX I

PLOTS OF METAL LOSSES AND CORRESPONDING STANDARD DEVIATIONS

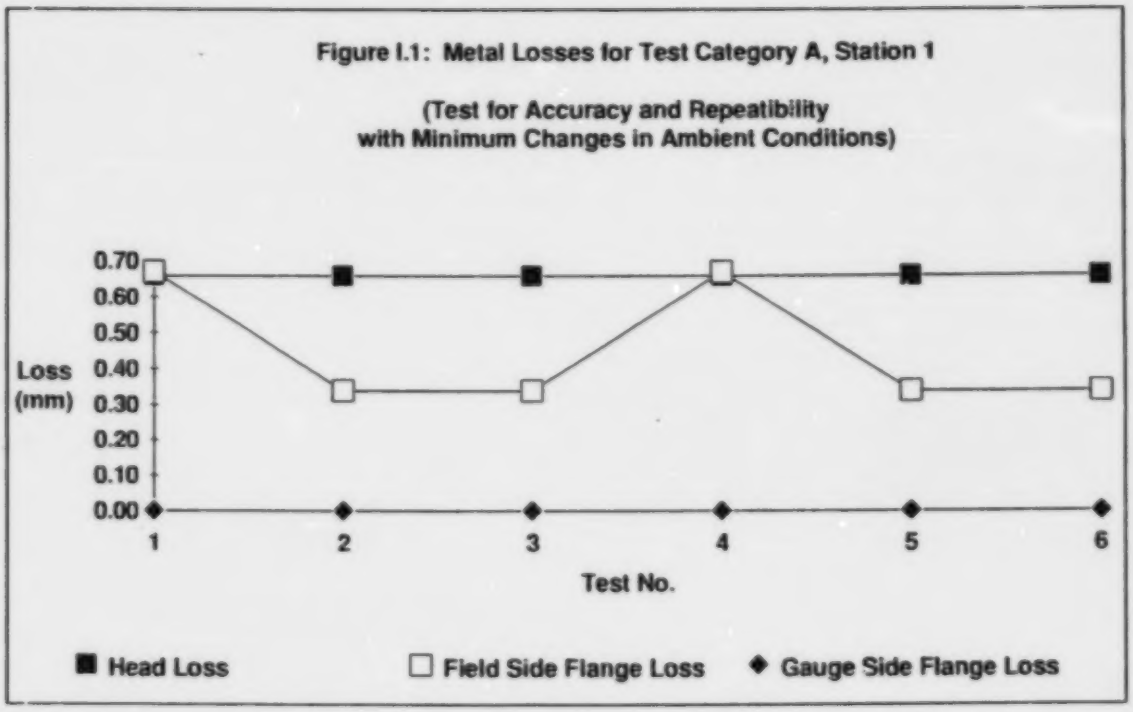
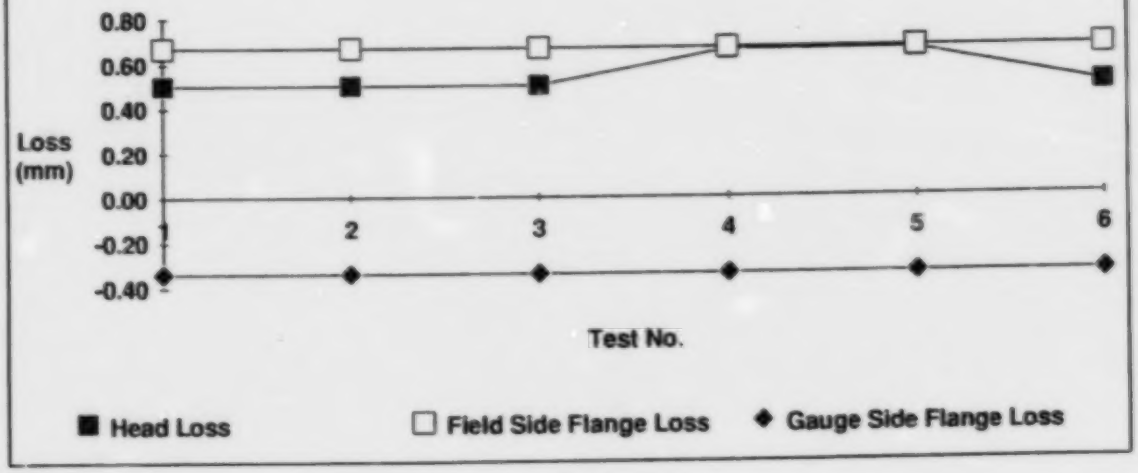


Figure I.1: Metal Losses for Test Category A, Station 1
(Test for Accuracy and Repeatibility
with Minimum Changes in Ambient Conditions)
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Loss
(mm)
1
2
3
4
5
6
Test No.
Head Loss
Field Side Flange Loss
Gauge Side Flange Loss

Figure I.2: Metal Losses for Test Category A, Station 2

(Test for Accuracy and Repeatibility
with Minimum Changes in Ambient Conditions)



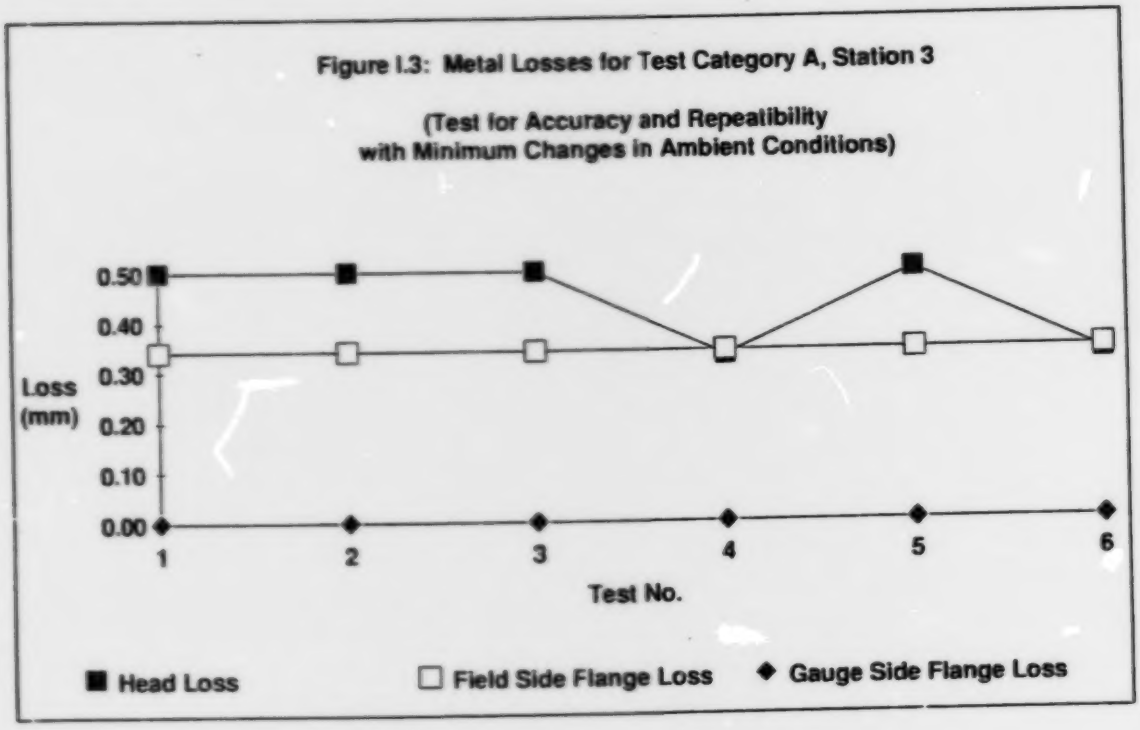


Figure I.3: Metal Losses for Test Category A, Station 3
(Test for Accuracy and Repeatibility
with Minimum Changes in Ambient Conditions)
Loss
(mm)
0.50
0.40
0.30
0.20
0.10
0.00
1
2
3
4
5
6
Test No.
Head Loss
Field Side Flange Loss
Gauge Side Flange Loss

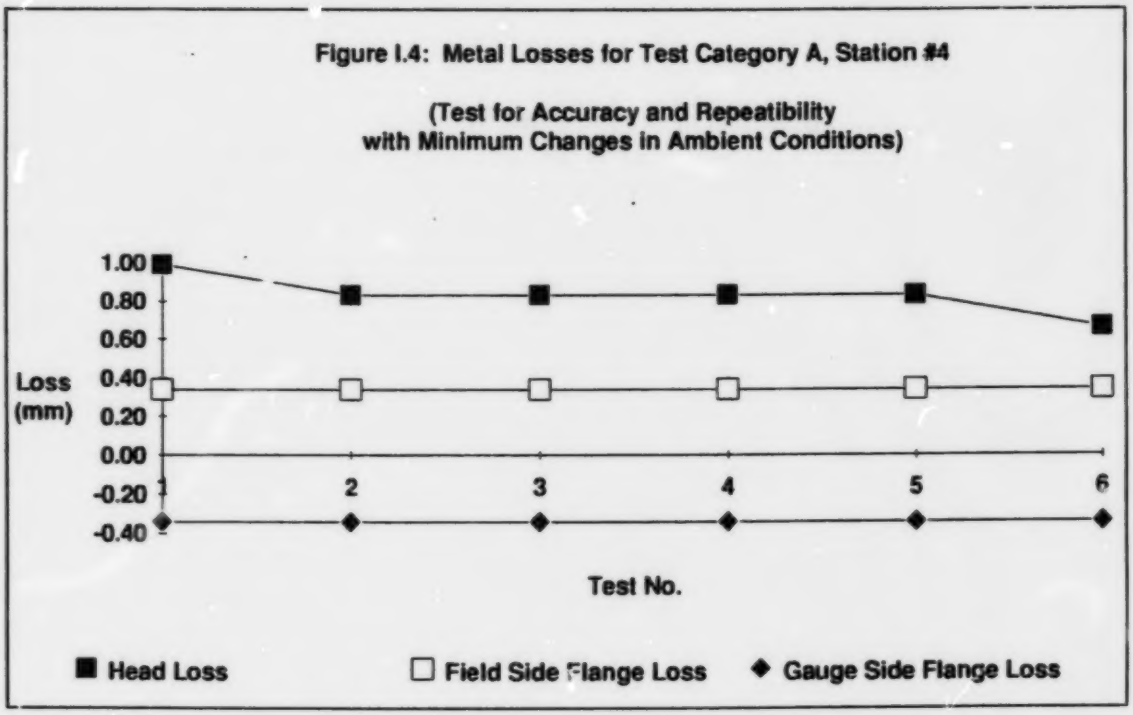


Figure I.4: Metal Losses for Test Category A, Station #4
(Test for Accuracy and Repeatibility
with Minimum Changes in Ambient Conditions)
1.00
0.80
0.60
0.40
0.20
0.00
-0.20
-0.40
Loss
(mm)
1
2
3
4
5
6
Test No.
Head Loss
Field Side Flange Loss
Gauge Side Flange Loss

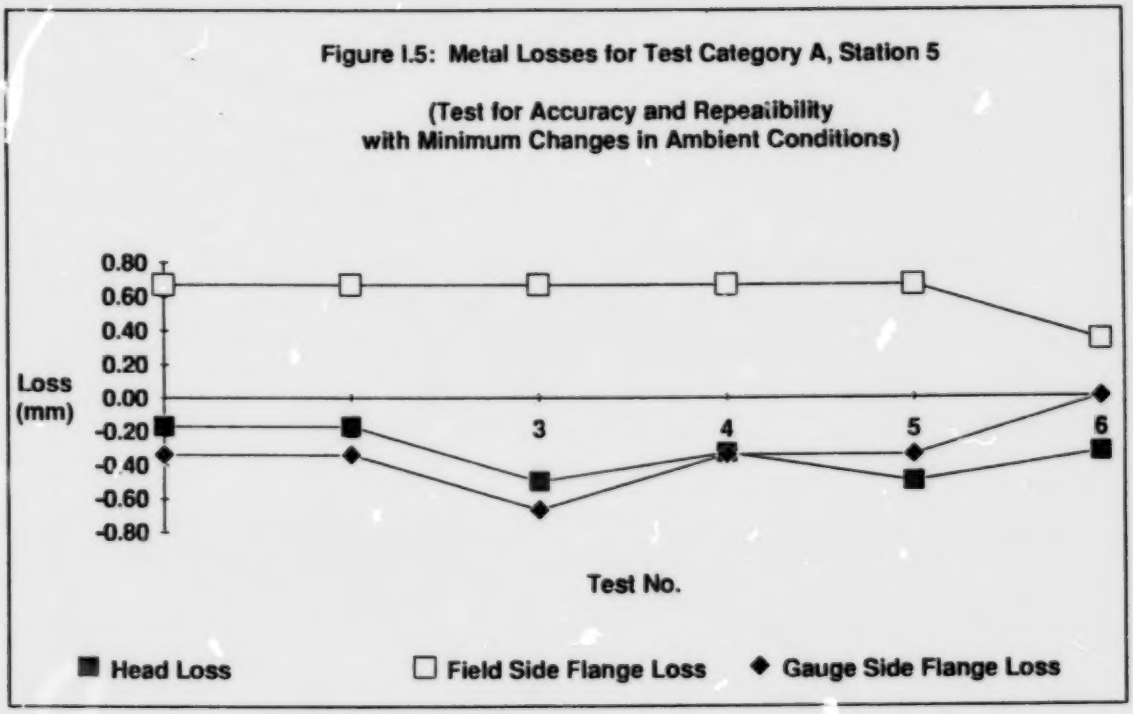


Figure I.5: Metal Losses for Test Category A, Station 5
(Test for Accuracy and Repeatibility
with Minimum Changes in Ambient Conditions)
0.80
0.60
0.40
0.20
0.00
-0.20
-0.40
-0.60
-0.80
Loss
(mm)
3
4
5
6
Test No.
Head Loss
Field Side Flange Loss
Gauge Side Flange Loss

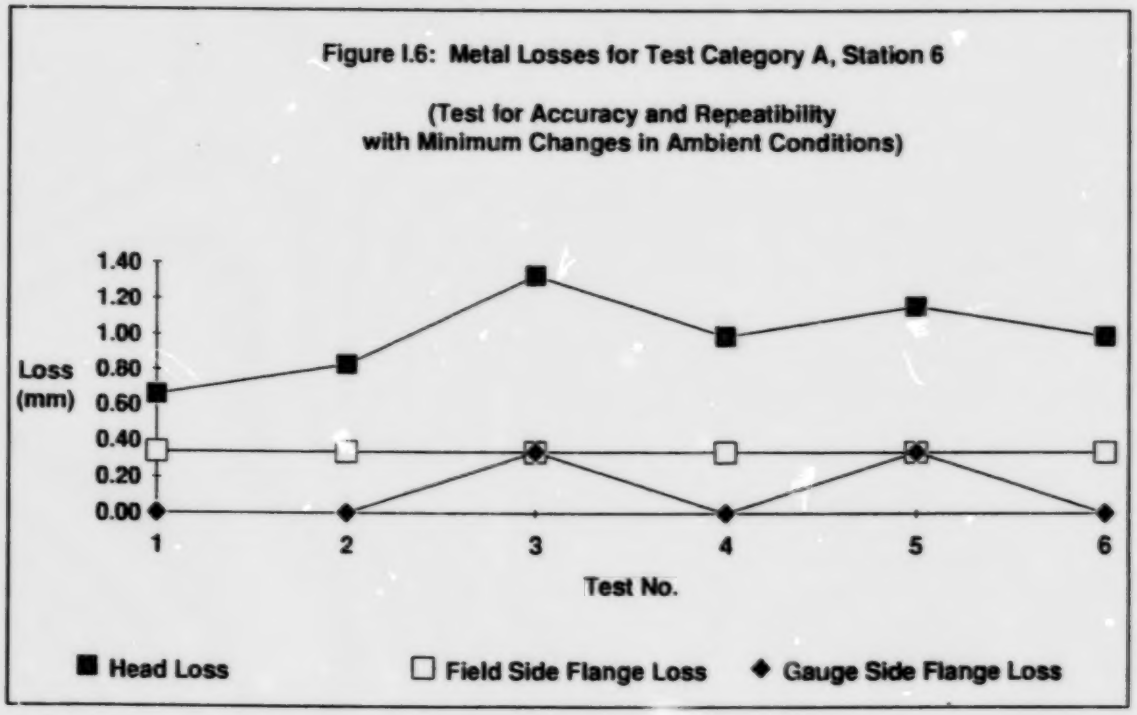


Figure I.6: Metal Losses for Test Category A, Station 6
(Test for Accuracy and Repeatibility
with Minimum Changes in Ambient Conditions)
Loss (mm)
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
1
2
3
4
5
6
Test No.
Head Loss
Field Side Flange Loss
Gauge Side Flange Loss

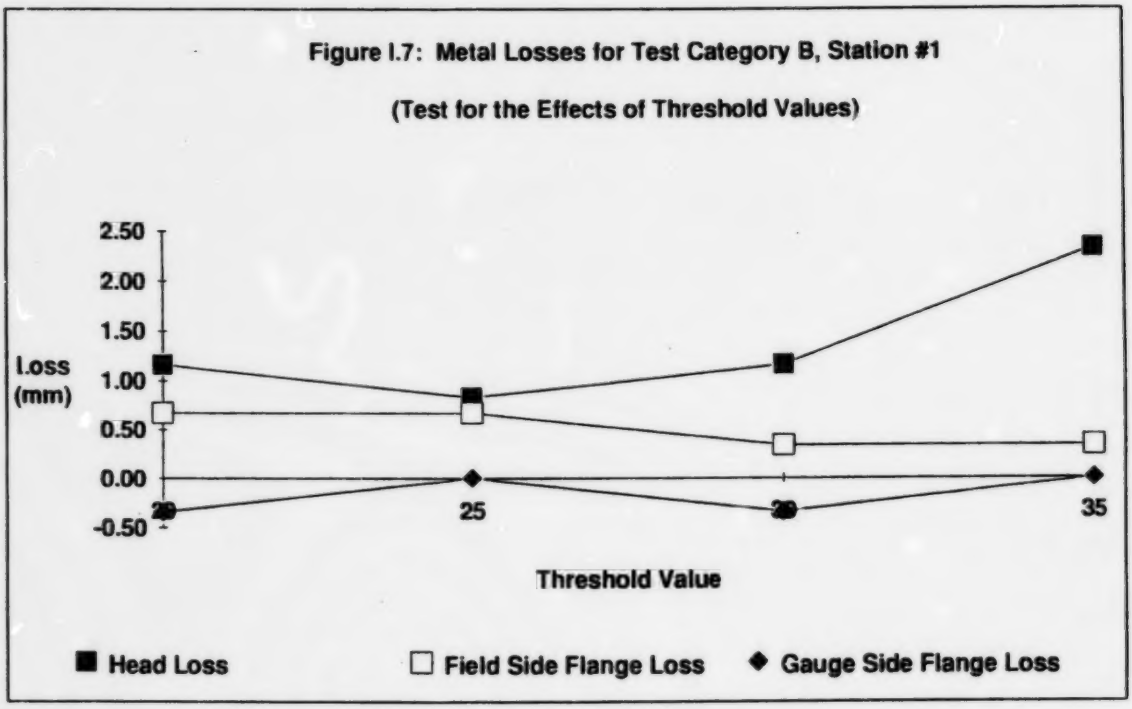


Figure I.7: Metal Losses for Test Category B, Station #1
(Test for the Effects of Threshold Values)
2.50
2.00
1.50
1.00
0.50
0.00
-0.50
I.oss
(mm)
25
35
Threshold Value
Head Loss
Field Side Flange Loss
Gauge Side Flange Loss

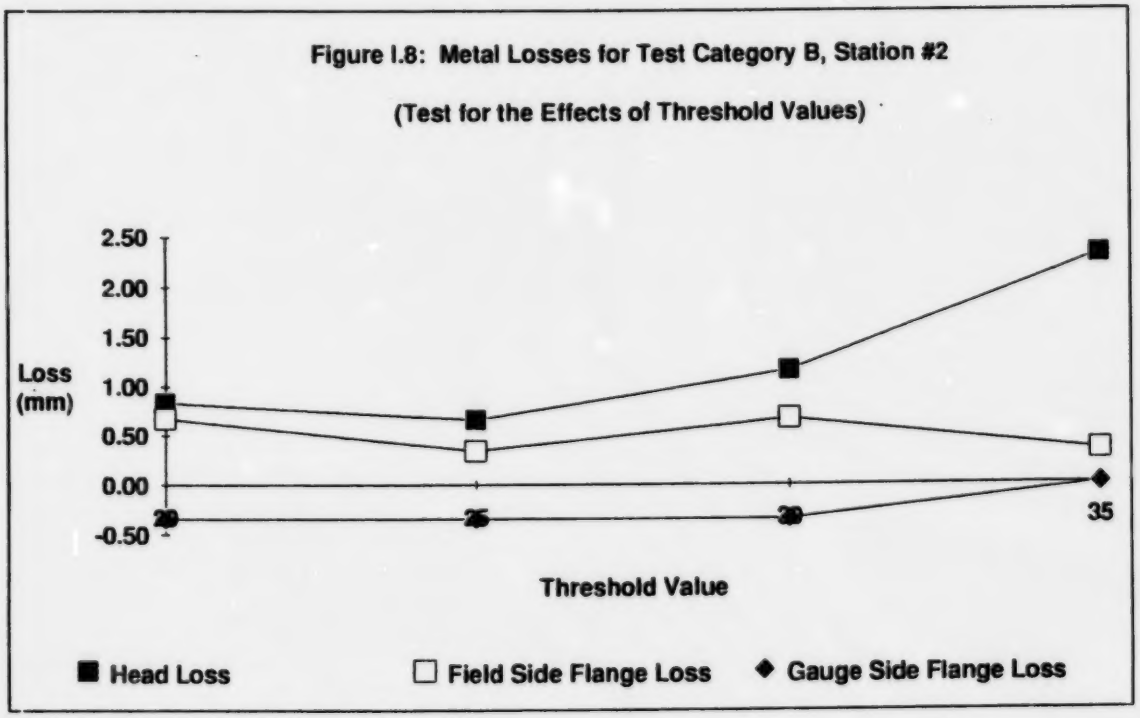


Figure I.8: Metal Losses for Test Category B, Station #2
(Test for the Effects of Threshold Values)
2.50
2.00
1.50
1.00
0.50
0.00
-0.50
Loss (mm)
35
Threshold Value
Head Loss
Field Side Flange Loss
Gauge Side Flange Loss

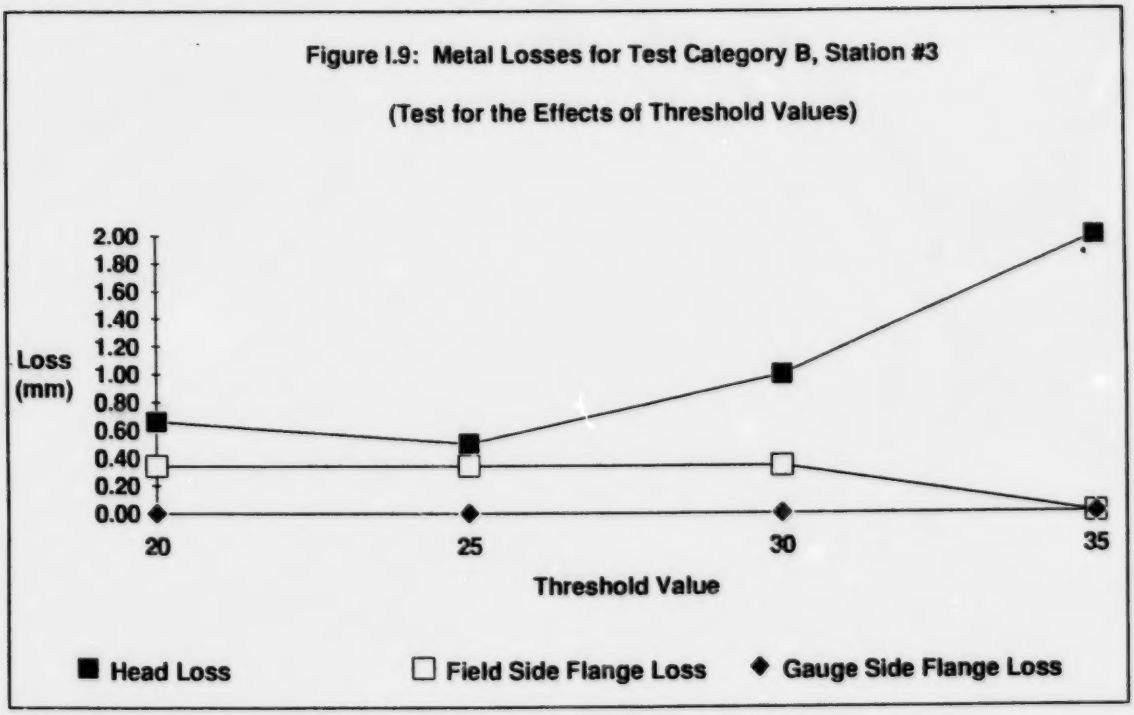


Figure I.9: Metal Losses for Test Category B, Station #3
(Test for the Effects of Threshold Values)
2.00
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
Loss (mm)
20
25
30
35
Threshold Value
Head Loss
Field Side Flange Loss
Gauge Side Flange Loss

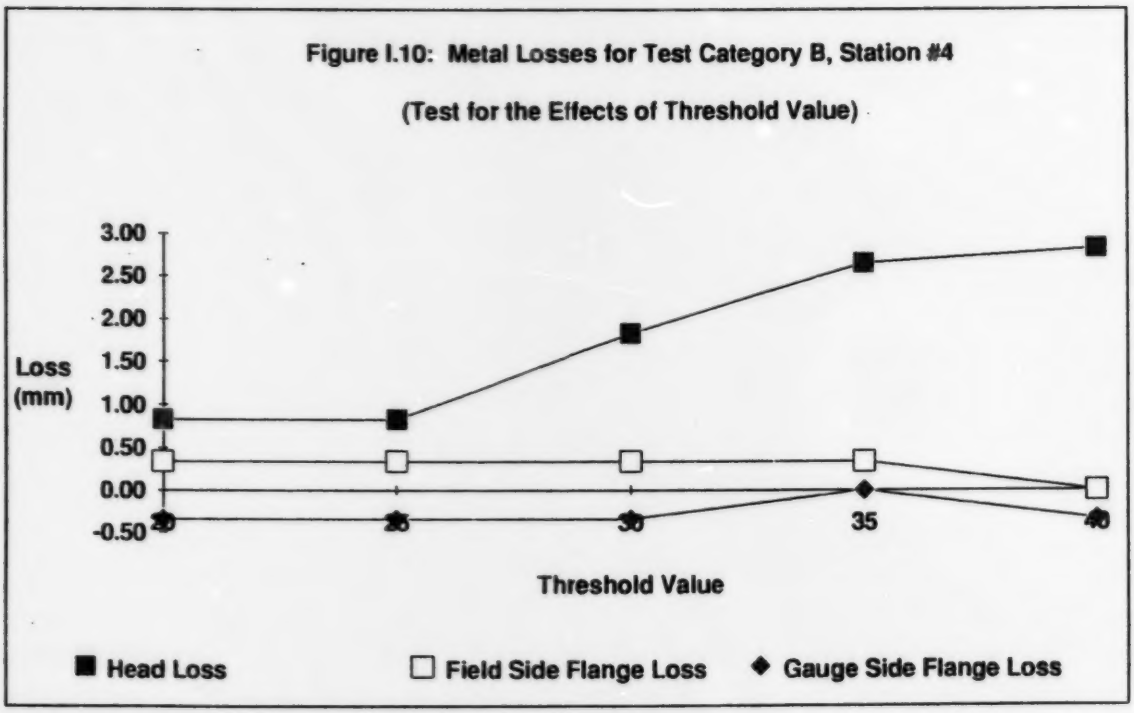


Figure I.10: Metal Losses for Test Category B, Station #4
(Test for the Effects of Threshold Value)
3.00
2.50
2.00
1.50
1.00
0.50
0.00
-0.50
Loss (mm)
35
Threshold Value
Head Loss
Field Side Flange Loss
Gauge Side Flange Loss

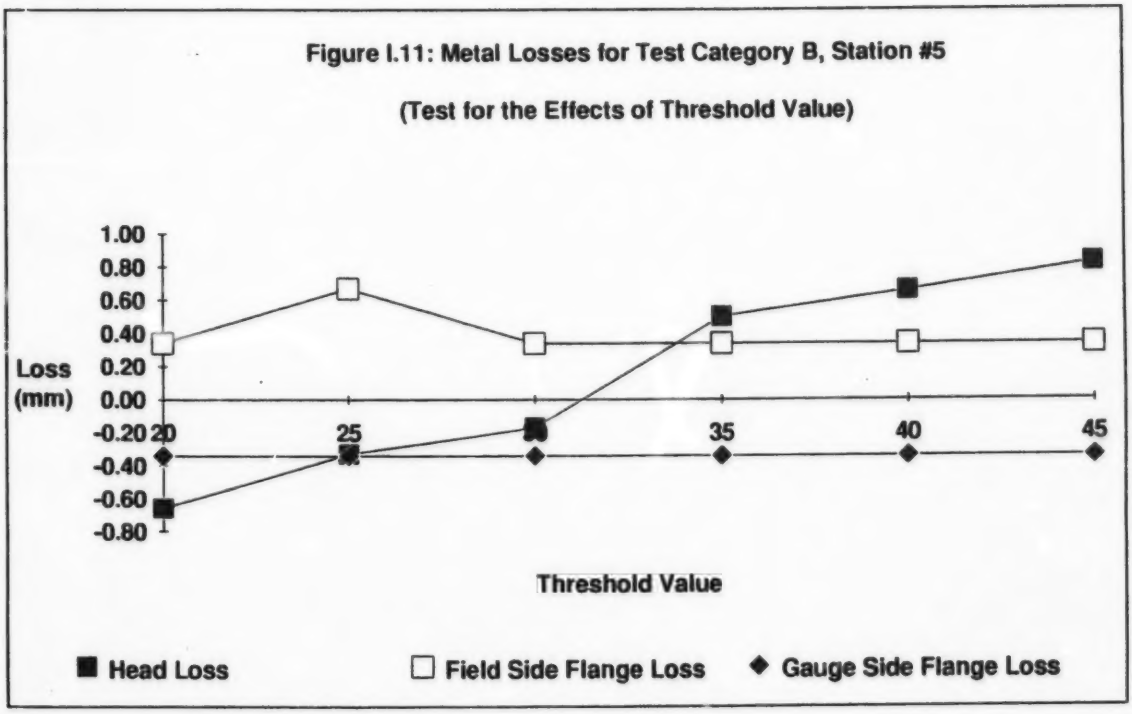


Figure I.11: Metal Losses for Test Category B, Station #5
(Test for the Effects of Threshold Value)
1.00
0.80
0.60
0.40
0.20
0.00
-0.20
-0.40
-0.60
-0.80
Loss
(mm)
20
25
35
40
45
Threshold Value
Head Loss
Field Side Flange Loss
Gauge Side Flange Loss

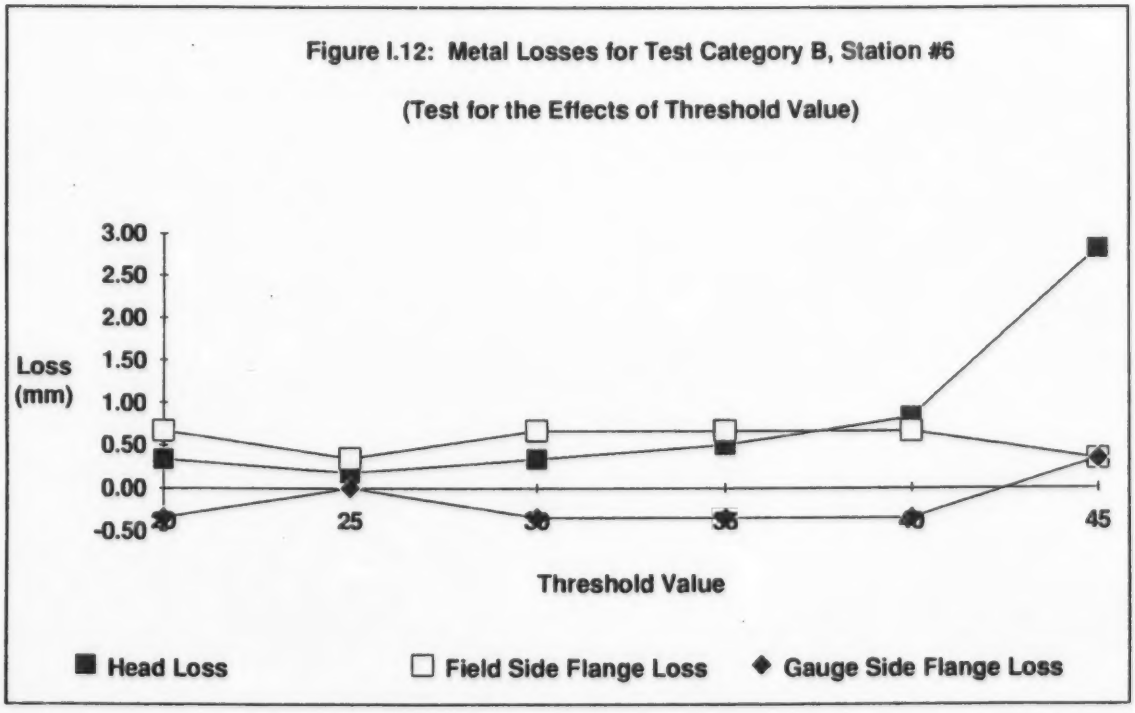


Figure I.12: Metal Losses for Test Category B, Station #6
(Test for the Effects of Threshold Value)
3.00
2.50
2.00
1.50
1.00
0.50
0.00
-0.50
Loss (mm)
25
45
Threshold Value
Head Loss
Field Side Flange Loss
Gauge Side Flange Loss

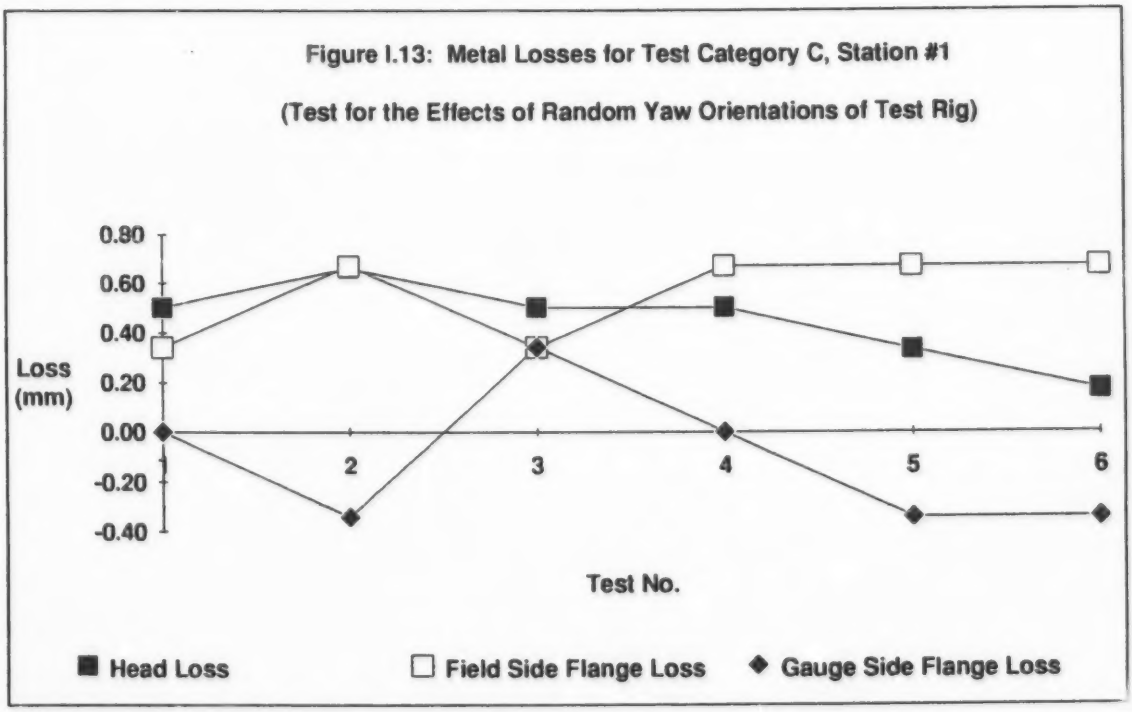
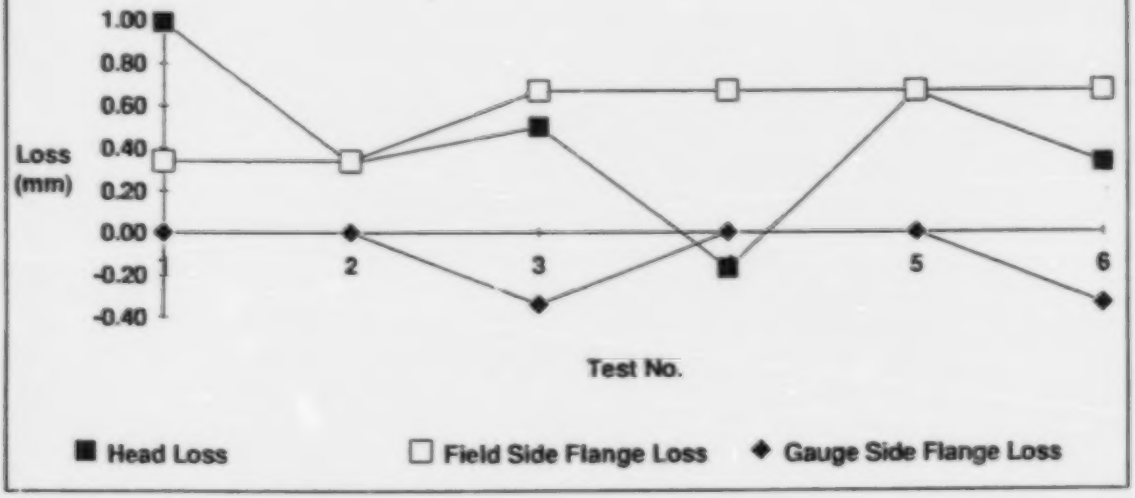


Figure I.13: Metal Losses for Test Category C, Station #1
(Test for the Effects of Random Yaw Orientations of Test Rig)
0.80
0.60
0.40
0.20
0.00
-0.20
-0.40
Loss (mm)
1
2
3
4
5
6
Test No.
Head Loss
Field Side Flange Loss
Gauge Side Flange Loss

Figure I.14: Metal Losses for Test Category D, Station #1

(Dynamic Operation Simulation)



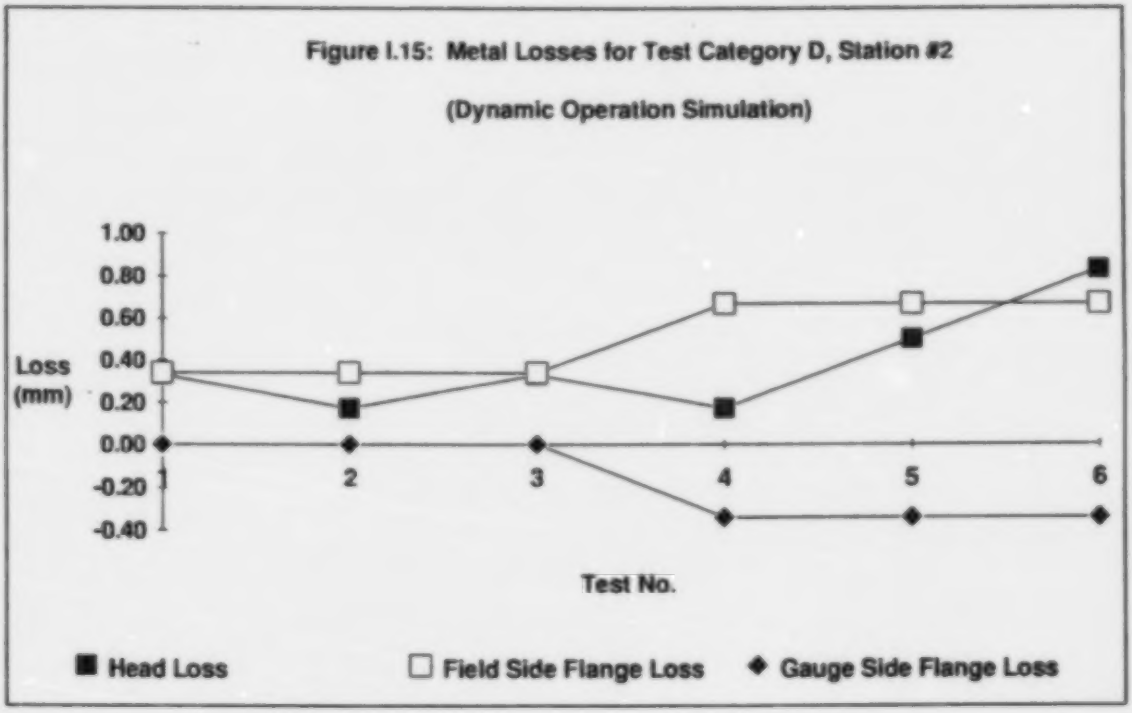


Figure I.15: Metal Losses for Test Category D, Station #2
(Dynamic Operation Simulation)
1.00
0.80
0.60
0.40
0.20
0.00
-0.20
-0.40
Loss (mm)
1
2
3
4
5
6
Test No.
Head Loss
Field Side Flange Loss
Gauge Side Flange Loss

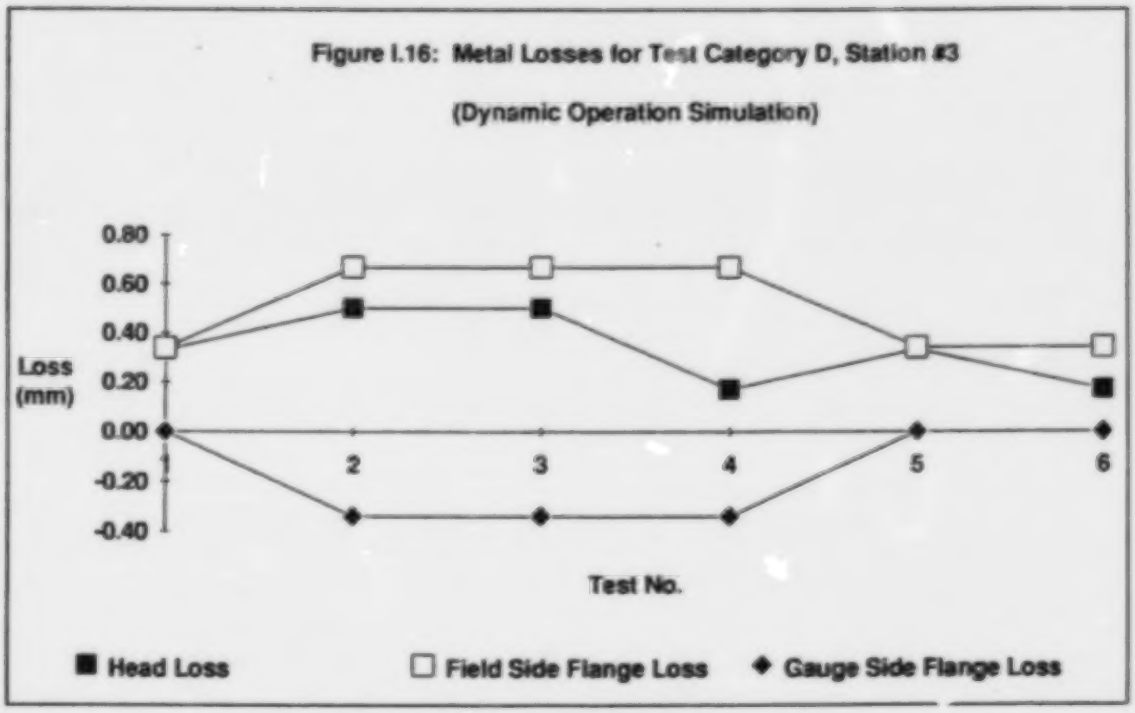


Figure I.16: Metal Losses for Test Category D, Station #3
(Dynamic Operation Simulation)
0.80
0.60
0.40
0.20
0.00
-0.20
-0.40
Loss (mm)
1
2
3
4
5
6
Test No.
Head Loss
Field Side Flange Loss
Gauge Side Flange Loss

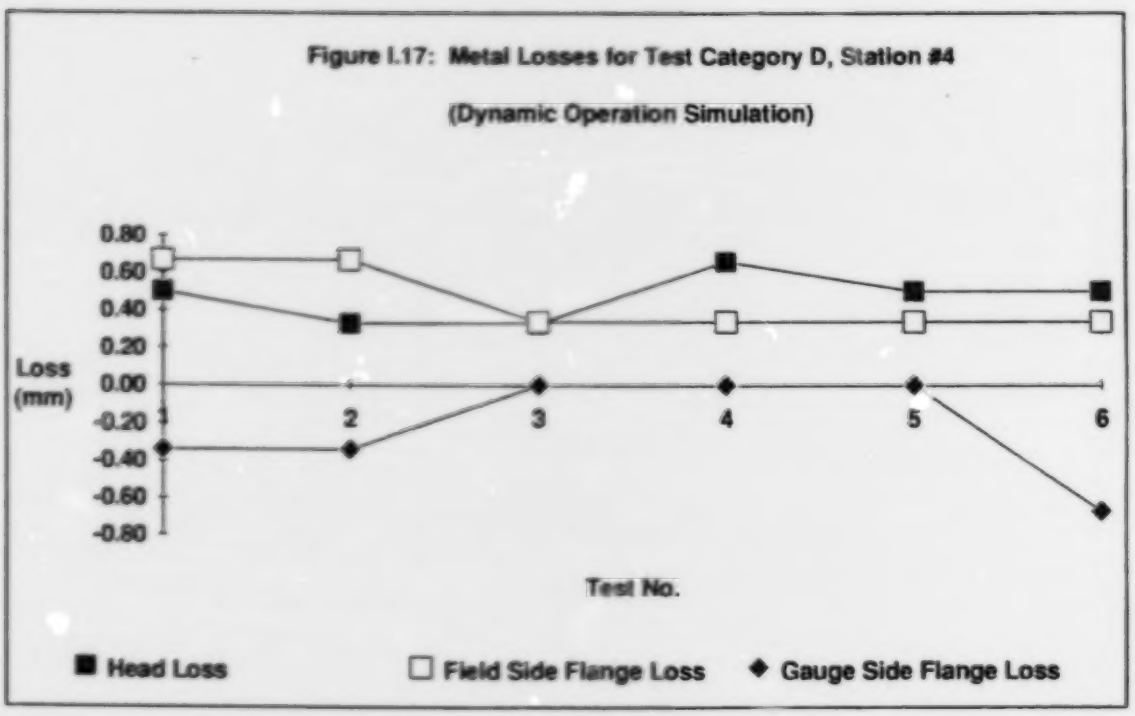


Figure I.17: Metal Losses for Test Category D, Station #4
(Dynamic Operation Simulation)
0.80
0.60
0.40
0.20
0.00
-0.20
-0.40
-0.60
-0.80
Loss (mm)
1
2
3
4
5
6
Test No.
Head Loss
Field Side Flange Loss
Gauge Side Flange Loss

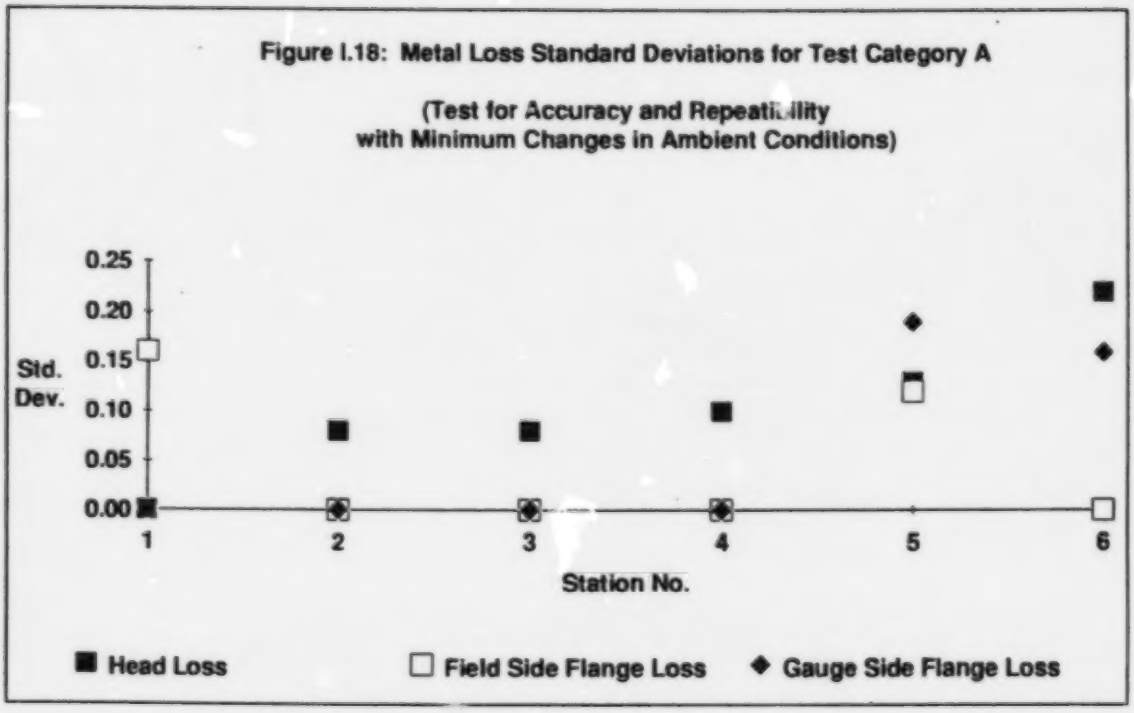


Figure I.18: Metal Loss Standard Deviations for Test Category A
(Test for Accuracy and Repeatability
with Minimum Changes in Ambient Conditions)
Std. Dev.
0.25
0.20
0.15
0.10
0.05
0.00
1
2
3
4
5
6
Station No.
Head Loss
Field Side Flange Loss
Gauge Side Flange Loss

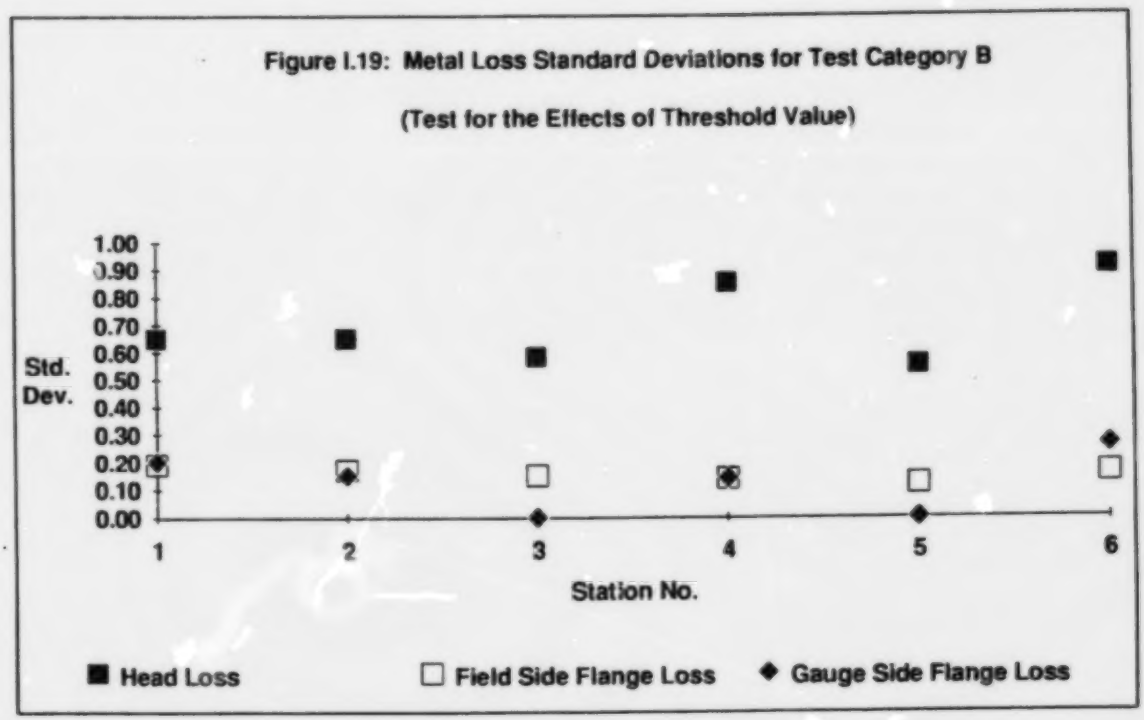


Figure I.19: Metal Loss Standard Deviations for Test Category B
(Test for the Effects of Threshold Value)
Std. Dev.
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
1
2
3
4
5
6
Station No.
Head Loss
Field Side Flange Loss
Gauge Side Flange Loss

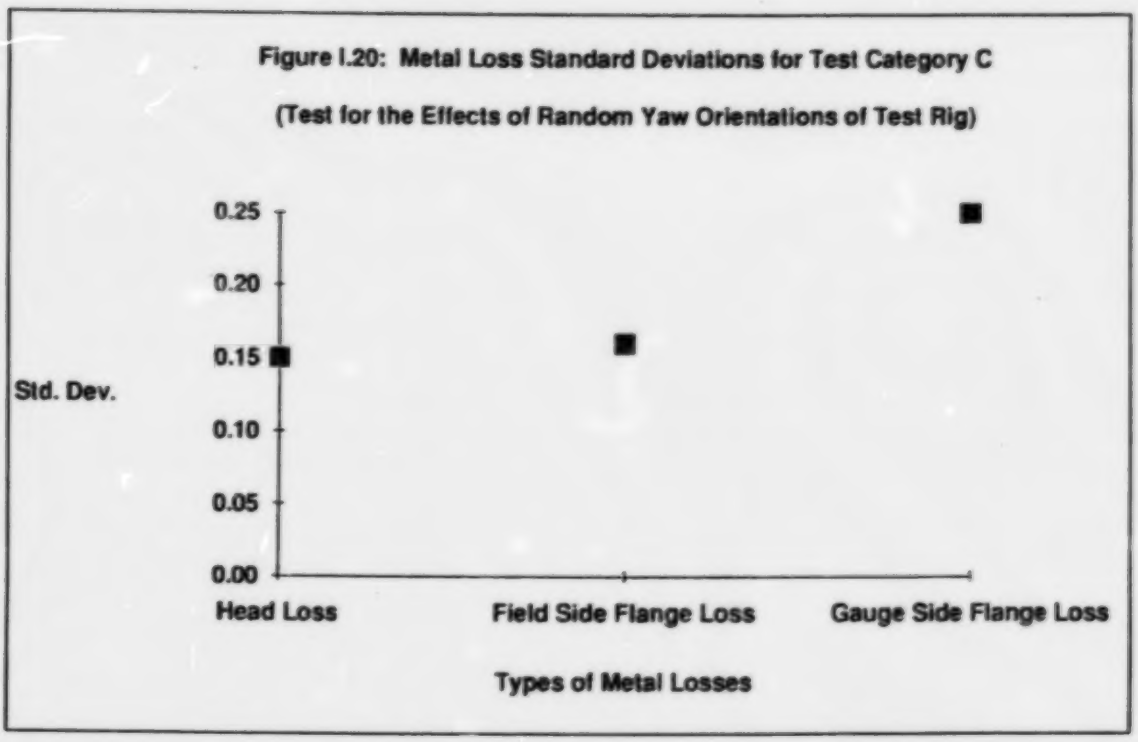


Figure I.20: Metal Loss Standard Deviations for Test Category C
(Test for the Effects of Random Yaw Orientations of Test Rig)
0.25
0.20
0.15
0.10
0.05
0.00
Std. Dev.
Head Loss
Field Side Flange Loss
Gauge Side Flange Loss
Types of Metal Losses

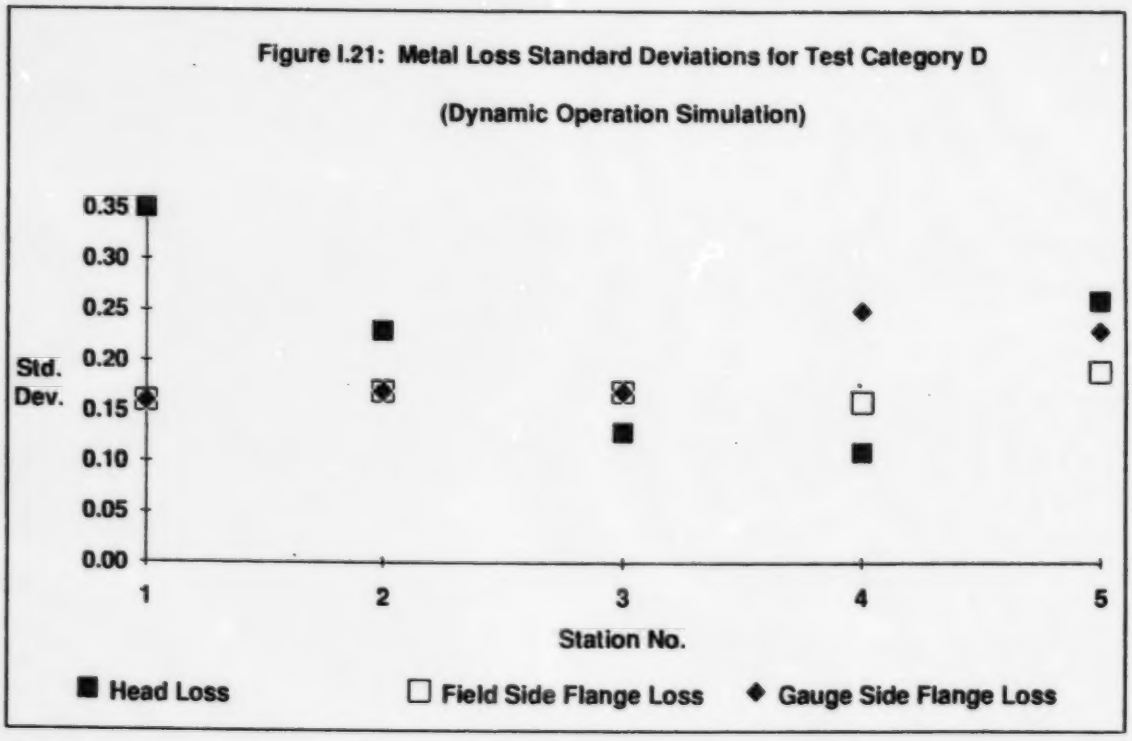


Figure I.21: Metal Loss Standard Deviations for Test Category D
(Dynamic Operation Simulation)
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
Std. Dev.
1
2
3
4
5
Station No.
Head Loss
Field Side Flange Loss
Gauge Side Flange Loss

APPENDIX II

PLOTS OF GOOD PROFILES

Test Category A : Station 1 : Test #4 (cas1t4.dat)

F1:RETURN F2:PRINT

Test Category B : Station 5 : Test 5 (chs5t5.dat)

F1:RETURN F2:PRINT

Test Category D : Station 1 : Test 1 (cd11.dat)

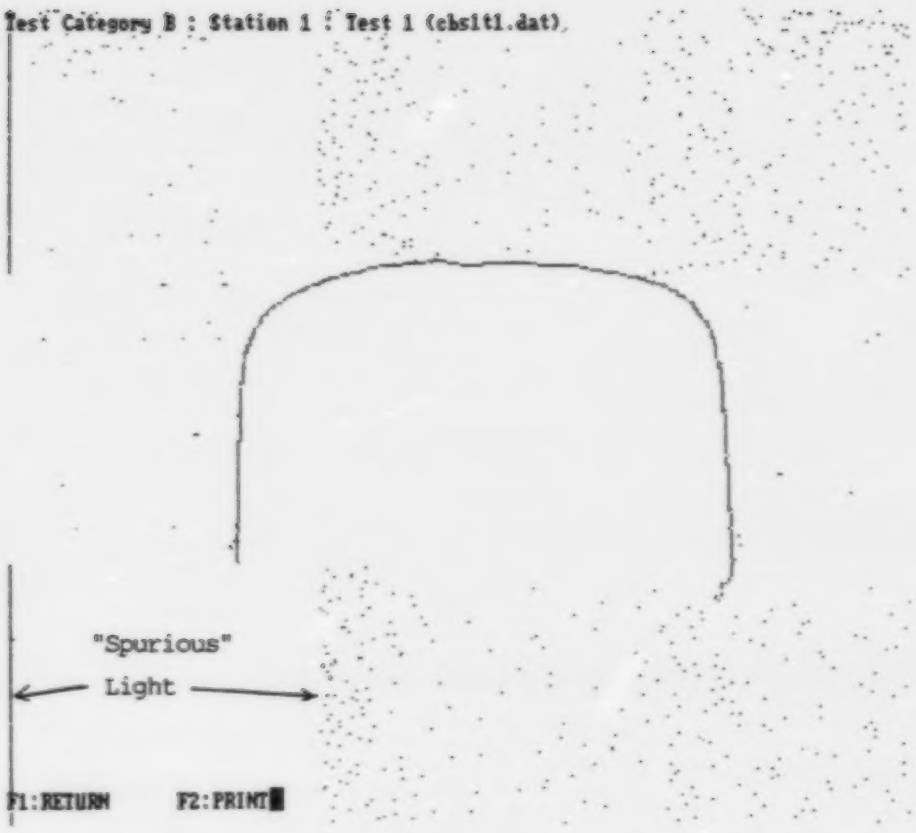
F1:RETURN F2:PRINT

Test Category C : Station 1 : Test 6 (ccs1t6.dat)

F1:RETURN F2:PRINT

APPENDIX III

PLOTS OF BAD PROFILES


Test Category B : Station 1 : Test 1 (cbs1t1.dat)
"Spurious"
Light
F1:RETURN
F2:PRINT

Test Category B : Station 3 : Test 7 (cbs3t7.dat)

(Incomplete Profile Definition)

F1:RETURN F2:PRINT